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VERIFICATION OF LANDSLIDE SUSCEPTIBILITY MAPPING: A CASE STUDY

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ABSTRACT

A methodology is proposed for mapping susceptibility to landsliding and validating the results. Heavy rains in late 1996 and early 1997 led to a large number of landslides in the Rute sector (Córdoba, Southern Spain), where landslide susceptibility mapping had previously been carried out using a 'matrix' method developed with a Geographical Information System (GIS). Analysis of the distribution of the new landslides (or reactivated earlier ones) enabled the methodology to be validated by calculating association coefficients and determining the closeness of the match between subsequent field evidence and the previously defined susceptibility levels. From the data obtained, it can be concluded that the susceptibility mapping effectively explained the spatial distribution of landslides, thus providing valuable information on stability conditions over a widespread area. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: landslides; susceptibility validation; GIS; Córdoba; Spain

INTRODUCTION

There are numerous methods for analysing landslide susceptibility, most of which are based on comparing determinant factors and the surface area distribution of the movements observed (Brabb *et al*., 1972; Nilsen *et al*., 1979; Chacón, 1988; Chacón *et al*., 1993, 1994; Baeza, 1994; Irigaray, 1995). All these approaches attempt to zone the stability conditions of slopes; however, it is not always possible to verify how useful these methods really are. In order to analyse the validity of such maps, they are sometimes compared with the same movements that were used to draw them up (Irigaray *et al*., 1996a; Baeza, 1994). This cross-validation procedure enables us to determine whether the susceptibility map adequately explains the distribution of past and present landslides, but tells nothing about what can be expected in the future. An alternative approach is proposed which enables the validity of the mapping to be contrasted against future landslides by comparing the earlier maps with the distribution of landslides which occurred subsequently.

The aim of the present study is to determine the reliability and usefulness of a landslide susceptibility map devised for the Rute sector in the province of Córdoba (Southern Spain) by means of the 'matrix method' (Irigaray *et al*., 1994; Irigaray, 1995). This has been developed using the SPANS Geographical Information System (TYDAC, 1993). Association coefficients have been calculated based on the closeness of the match between the movements generated as a consequence of the heavy rains in late 1996 and early 1997 together with previously defined susceptibility levels.

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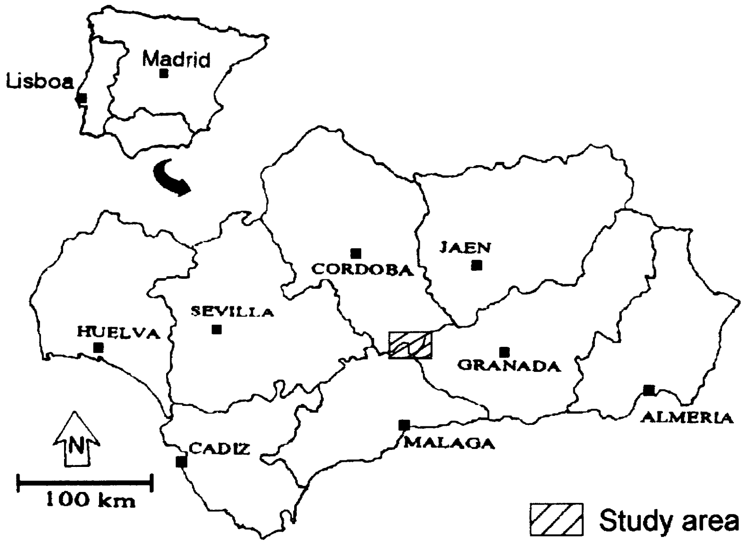

Figure 1. Location of the study area

The study area roughly coincides with Sheet 1007 (Rute) of the 1:50 000 Spanish National Topographical Map. It lies at the confluence of the Southern Spanish provinces of Córdoba, Granada and Málaga, delimited by the geographical coordinates 37° 10′ 18″–37° 20′ 07″ N and 4° 11′ 18″–4° 31′ 06″ W, and covers an area of approximately 503 km^2 (Figure 1). The area is crossed from E to W by the river Genil, whose flow is controlled by the Iznájar dam, impounding a reservoir which has a maximum extent of around 30 km^2.

Most of the geological outcrop falls within the External Zones of the Betic Cordillera mountains – more specifically, in the Mid-Sub-Betic ranges (Fallot, 1948), along with the presence of Triassic Keuper facies materials (Blumenthal, 1931). As a result of tectonic activity, units from the Campo de Gibraltar are also present (Fallot, 1948; Martín Algarra, 1987), described as 'Presdorsalian Flysch' of the 'Circum-Betic Zone' and 'Tecto-sedimentary Formations' (Cano, 1990).

LANDSLIDE SUSCEPTIBILITY ASSESSMENT

Landslide susceptibility can be defined as the tendency for a landslide to be generated in a specific area in the future; this can be measured from the correlation between determining factors together with the spatial distribution of the movements (Brabb, 1984).

Determining factors

The determining factors used for this study were altitude, slope angle, aspect, illumination coefficient, vertical curvature, landforms, lithological characteristics, tectonic units, mean annual rainfall, vegetation and the drainage network (Irigaray, 1995; Irigaray *et al.*, 1996b).

Pre-1995 landslides

The landslide inventory used for the susceptibility of movements was generated before 1995. A system of classification based on Varnes (1978) was applied, whereby three basic movement types are distinguished: *rock falls, slides* and *flows*. The 'flows' category was in turn subdivided into three

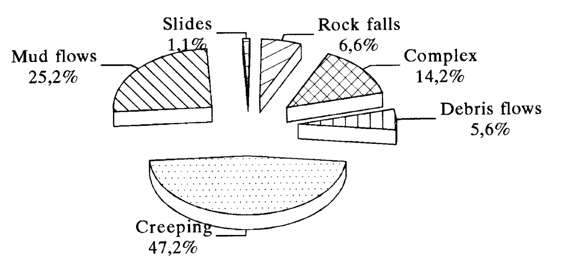

Figure 2. Surface area distribution according to pre-1995 landslide types

subcategories: *creeping areas, mud flows* and *debris flows* (Corominas, 1989). Movements were considered to be *complex* if they resulted from a combination of two or more of the three main types. There are as many types of complex movement as there are possible combinations of simple movements.

The first stage in compiling the inventory consisted of interpreting the 1:18 000-scale stereoscopic aerial photographs. Once the movements had been mapped, a field campaign was carried out in order to verify the typology of each movement and collect further data (e.g. on activity, make a photographic record, take samples, etc.). The final inventory based on the aerial photographs was then converted to digital TYDIG format (TYDAC, 1993), introducing the appropriate number of control points in order to optimize the adjustment. These data were subsequently exported to the SPANS Geographical Information System (TYDAC, 1993).

In the study sector 800 movements were recorded: 92 rock falls, 46 slides, 380 mud flows, 129 creeping areas, 109 debris flows and 44 'complex' movements. The area affected by landslides (52·1 km^2) represents 10·4 per cent of the total surface area. The surface area distribution for each movement type is shown in Figure 2. Creeping phenomena accounted for not only nearly 50 per cent of all the surface area affected, but also the largest of the landslides recorded (19·1 ha per movement of average area). Mud flows represented 25·2 per cent of the movements, with an average area of 3·4 ha per movement. With 16·9 ha per movement, complex movements were in third place in terms of the total surface area occupied (14·2 per cent) and in second place in terms of the average area. Rock falls represented 6.6 per cent of the surface area of the movements, with an average area of 3·7 ha per movement. Slides and debris flows together represented only 6·7 per cent of the total movements, with 1·3 and 2·7 ha per movement respectively; they were also the movement types with the smallest average area (Irigaray, 1995).

Susceptibility analysis methodology

The matrix method (DeGraff and Romesburg, 1980; Irigaray, 1995) is a quantitative method for establishing an instability index for a given area. Although it cannot predict the landslide susceptibility in terms of absolute probability, it does enable relative potential instability to be calculated for a widespread area using a series of measurable factors.

Once a set of factors has been identified which can condition the appearance of landslides, a matrix is constructed with each cell representing one possible combination of the classes of factors considered. From the landslide inventory, the area affected by movements can then be calculated for each combination of factors. The result is a landslide matrix (Figure 3A). A similar procedure is used to construct the management unit matrix, representing the total area for each combination of factors (Figure 3B). The landslide-susceptibility matrix has the same number of combinations as the management unit matrix (Figure 3C). The value of each cell in this new matrix is obtained by dividing the values from the landslide matrix by those from the management unit matrix. Combinations that are not associated with landslides are assigned a value of '0' on the landslide-susceptibility matrix; the

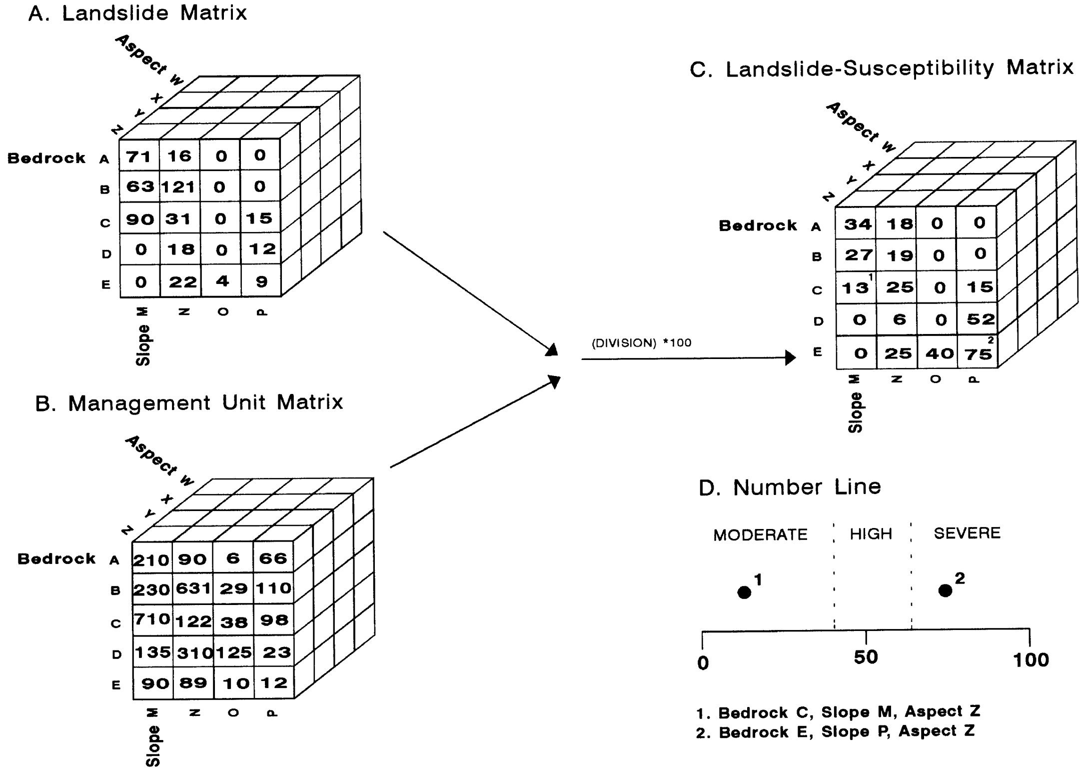

Figure 3. Measurement of landslide susceptibility using the 'matrix' method (after DeGraff and Romesburg, 1980)

remainder will have values of >0, up to a maximum of 1 (or 100 per cent, if expressed as a percentage).

The susceptibility matrix values represent the proportion of landslides as a function of the total area, and represent the relative susceptibility of each combination of factors. Since any given point in the study area is characterized by a certain combination of factors, the relative susceptibility at that point will be the one corresponding to that combination within the susceptibility matrix.

This methodology was developed using the SPANS Geographical Information System (TYDAC, 1993). Figure 4 shows the landslide susceptibility map, divided into five categories (*very low, low, moderate, high, and very high*). Surfaces classified as being of 'high' or 'very high' susceptibility account for 15·1 per cent of the study area. 'Low' or 'very low' susceptibility accounts for 58·3 per cent, whereas 'moderate' susceptibility covers 26·6 per cent of the total area (Figure 5). These values indicate that this map is not conservative, but rather limits the areas of maximum susceptibility to a relatively small area in comparison with other analytical methods like 'critical slope angle', 'indexing', 'value of information' or 'multiple regression' (Irigaray, 1995; Irigaray *et al.*, 1996a).

VERIFICATION OF THE SUSCEPTIBILITY MAP

In order to verify the applicability of the proposed method, certain association coefficients were calculated between the susceptibility map and the inventory of the landslides that occurred during the heavy rains of late 1996 and early 1997 (i.e. a considerable time after the susceptibility map was constructed). The closeness of match between the mapped landslides and the different levels of susceptibility was also determined.

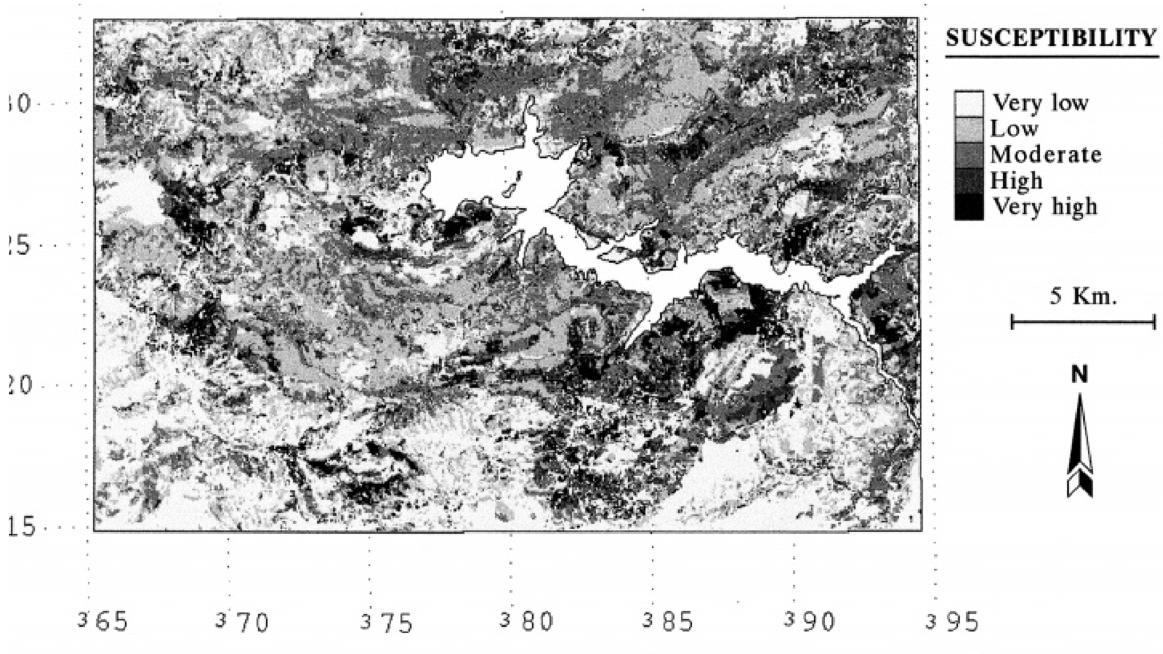

Figure 4. Landslide susceptibility map computed by the 'matrix' method

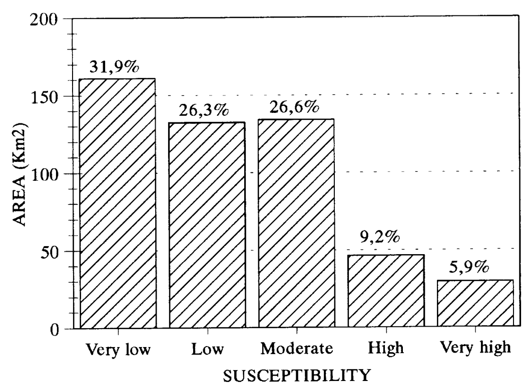

Figure 5. Frequency histogram for each susceptibility level

Landslides resulting from the heavy rains of the 1996/97 winter

As a consequence of heavy rains in the study area in late 1996 and early 1997 (117 mm in November 1996, 241 mm in December and 197 mm in January 1997, i.e. the mean annual rainfall for the area reached in only three months), 125 landslides were recorded, covering a total surface area of 2·8 km^2 . The 1996/97 landslides were inventoried and analysed following the same methodology used for the pre-1995 landslides. These movements can be broken down (Figure 6) into one rock fall (0·2 per cent of the surface inventoried), 14 slides (2·1 per cent), 74 mud flows (47 per cent), 27 creeping areas (43·4 per cent), one debris flow (0·3 per cent) and eight complex movements (6·9 per cent). This inventory is hereafter referred to as 'the '97 inventory'. Figure 7 shows a map of the landslide locations (pre-1995 landslides and the '97 inventory.

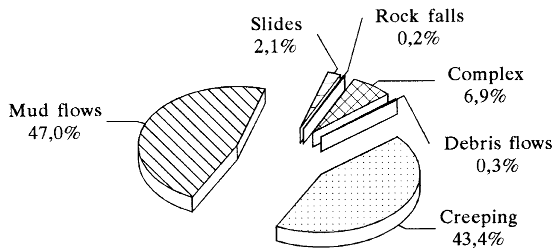

Figure 6. Surface area distribution according to 'the '97 inventory' type

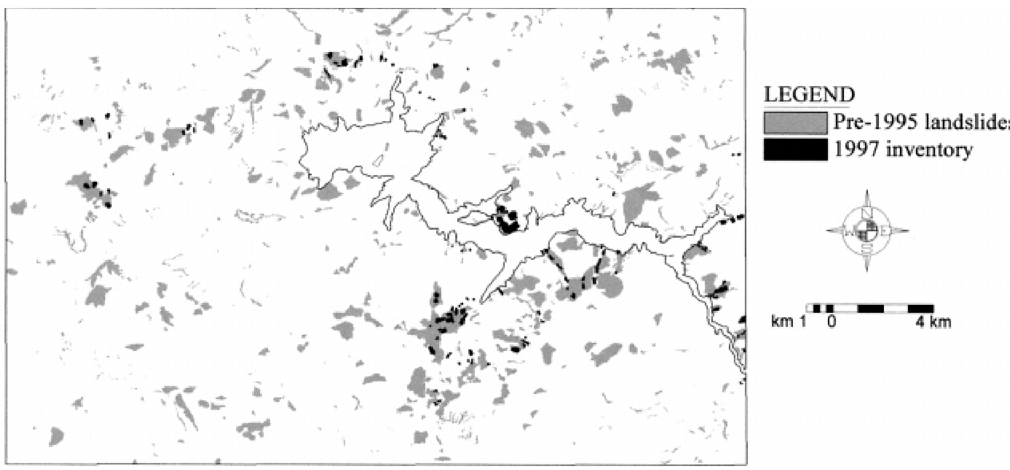

Figure 7. Map of the landslide locations

Association coefficients

The analysis consisted of determining the relationship between the susceptibility map and 'the '97 inventory'. A contingency table was devised for the surface area distribution of the movements, which could be differentiated for each of the susceptibility levels (Table I). In order to assess the degree of significance for the relationship, the Goodman–Kruskal gamma (γ) and Kolmogorov–Smirnov (K–S) test (Goodman and Kruskal, 1954; Goodman, 1954) were used. The γ value provides a robust measurement of the relationship between the variables; values over 0·5 indicate a significant association. The K-S test may be used to contrast the differences between two samples of independent observations, and so determine whether they originated in populations having the same distribution (CEOTMA, 1984).

The γ value obtained (0·67) and a confidence level of 99 per cent according to the K–S test, indicate a very close link between the '97 inventory and the susceptibility level.

Closeness of match

The contingency table (Table I) shows the area in (km^2) of the movements observed at the different susceptibility levels (m_i); the total area was classified as having an overall susceptibility level of t_i. The quotient between the m_i/t_i ratio for a given level i and the total sum $\Sigma m_i/t_i$ multiplied by 100, shows the relative distribution of the movements; this is the one which best defines the closeness of the match (Baeza, 1994) between the inventory and the susceptibility calculated.

Table I. Contingency table between the susceptibility map (columns) and the '97 inventory (rows)

	Very low	Low	Moderate	High	Very high	Total
No landslides						
Area (km^2)	160·636	132·217	133·319	45·755	28·582	500·508
Total (%)	31·91	26·27	26·49	9·09	5·68	99·44
Row	32·09	26·42	26·64	9·14	5·71	
Column	99·84	99·88	99·42	98·70	96·51	
Landslides						
Area (km^2)	0·258	0·163	0·770	0·605	1·034	2·829
Total (%)	0·05	0·03	0·15	0·12	0·12	0·56
Row	9·10	5·75	27·23	21·38	36·54	
Column	0·16	0·12	0·57	1·30	3·49	
Total	160·894	132·380	134·089	46·360	29·615	503·337
	31·97	26·30	26·64	9·21	5·88	

Contingency coefficient: 0.1078
Tschuprow's *T*: 0.0767
Cramer's *V*: 0.1085

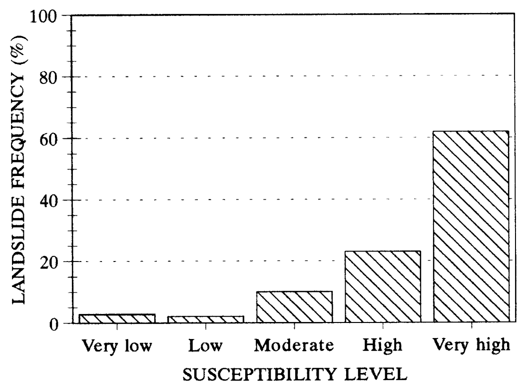

Figure 8. Relative frequency histogram expressing the closeness of match between the susceptibility map and 'the '97 inventory'

Classification of movement according to different susceptibility levels reveals the usefulness of the proposed mapping method. For example, if most of the recorded movement is classified unrealistically as having 'very low' or 'low' susceptibility, then the method would not be capable of reproducing the conditions of instability; in contrast, if most of the recorded movement falls within one of the higher categories ('moderate', 'high' or 'very high'), then this would indicate a closer match of the technique with the real instabilities observed.

The results obtained from Southern Spain (Figure 8) show that nearly 85 per cent of the movements recorded in the '97 inventory could be classified within the 'high' and 'very high' susceptibility categories. Under 5 per cent of the movements were classified in the 'low' or 'very low' categories, and most of these correspond to minor slides occurring on artificial banks, whose characteristics had not been considered in the inventory. The Spanish example demonstrates a good correspondence between the predicted results obtained using the matrix method and subsequent field observations.

CONCLUSIONS

Association coefficients have been derived using a matrix method to compute susceptibility to landsliding. The closeness of the match with the movement inventory demonstrates that the proposed

method offers an efficient explanation for the spatial distribution of the slope movements. Such maps have the potential to provide valuable information concerning the stability conditions over widespread areas, and would be of considerable use during both the planning and execution stages of major civil engineering projects enabling appropriate preventive measures to be incorporated in the works.

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